Dissociating semantic integration and inhibitory control in the Remote Associates Test: a tDCS-EEG study

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Abstract

Neuromodulation was utilized here to investigate the distinct involvement of two recognized cortical hubs for semantic integration (the left anterior temporal lobe, lATL) and inhibitory control (the right dorsolateral prefrontal cortex, rDLPFC) in creative problem-solving. Participants were presented with a list of category-exemplar words, selectively recalled some of them, and then solved a set of RAT problems. Selective retrieval was introduced to trigger inhibitory control over competitors. Critically, some RAT problems could be solved with words from the previous phases of the experiment, including words that might be less accessible due to inhibition. Other problems, however, could only be solved with unpresented words. Experiment 1 showed that anodal tDCS over the lATL had a negative effect on the production of correct responses to baseline RAT problems, but not on those that required inhibited solutions. Experiment 2 produced the reverse pattern with cathodal tDCS over the rDLPFC. Resting-state EEG recordings were obtained before and after delivering tDCS, which also revealed specific tDCS-induced changes in frequency bands depending on the site of stimulation. Overall, these findings provide support for the involvement of semantic and control processes in creative problem solving that are linked to different brain networks.

Keywords: creativity, semantic integration, inhibitory control, anterior temporal lobe, dorsolateral prefrontal cortex.

Introduction

Creativity is thought to be a hallmark of human beings and closely linked to success and evolution (Lindell, 2010). Hence, significant interest has been directed towards comprehending the neurocognitive underpinnings of creative thinking (Gerver et al., 2023; Cogdell-Brooke et al., 2020; Wu et al., 2020). Creativity is defined as the ability to generate novel, original and useful ideas or solutions to problems (Mednick, 1962). Relevant theoretical accounts on creativity, such as the dual-processes model, acknowledge the dynamic interplay between associative and controlled processes (Sowden et al., 2019; Volle, 2018). During the creative ideation, it is assumed that associative and spontaneous processes are responsible for the semantic activation of remotely related pieces of information, which are then combined into new ideas (or solutions; Beaty & Kenett, 2023; Kounios & Beeman, 2014). However, for these ideas to genuinely exhibit novelty and originality, it is necessary to avoid habitual thinking paths and dominant information in memory (Luft et al., 2018). Consequently, controlled and goal-directed processes are thought to play a central role in the downregulation of prepotent or interfering information/responses (Benedek et al., 2012; Lezama et al., 2023). Hence, semantic activation/integration and (inhibitory-like) control processes are thought to play an essential role during creative thinking (Benedek & Jauk, 2018).

Previous studies have underscored the importance of semantic memory structure in associative search processing and the role of inhibitory control in selecting original ideas (Beaty et al., 2022; Ovando-Tellez et al., 2022). When tackling creative problems, a search in semantic memory is initiated to find suitable pieces of information that can be integrated to reach a proper solution (Smith et al., 2013). A number of studies suggest that individuals with higher creativity tend to have semantic networks characterized by more broadly and strongly interconnected nodes of information (Benedek et al., 2017; Kenett et al., 2016) and fewer modules of distinct subnetworks, compared to less creative individuals (Denervaud et al., 2021; He et al., 2020). In addition, the ability to circumvent evident and irrelevant ideas that usually arise during the search process appears to facilitate the generation of more creative solutions (Lezama et al., 2023; Smith &

Blankenship, 1991; see Cassotti et al., 2018 for a review). Thus, for example, Storm and colleagues (Storm et al., 2010; Storm et al., 2011) demonstrated that individuals who exhibited enhanced inhibition of interfering episodic information also exhibited superior performance on a creativity test.

Of special interest here, Lezama et al. (2023) have recently demonstrated that better semantic activation of strong associates and better ability to inhibit episodically interfering information predicted superior performance on the Remote Association Test (RAT). The RAT is a verbal creativity task wherein triplets of unrelated words (e. g. manners-tennis-round) are presented and participants have to find a fourth word which relates to all of them (e.g., table) (Mednick, 1968). In Lezama et al.'s study, participants firstly performed a lexical decision task with strong and weak semantic associations between primes and target as well as an attentional (global-local) task. Participants then completed an adapted version of the selective retrieval (SR) procedure; for a recent review see Anderson & Hulbert 2021), which included a RAT as the final test (see Gómez-Ariza et al., 2017). Specifically, participants studied pairs of lexical category-exemplar (e.g., FA-Famous, FA-Factory, CA-Cathedra, CA-Canary) and, in a second phase, they selectively retrieved half of the words of half of the categories when the categories and word stems were provided as retrieval cues (e.g., CA-Can__). Since selective retrieval has been shown to trigger inhibitory control over competitors, making them less retrievable temporarily, this manipulation was introduced to increase the accessibility of practiced words (e. g. Canary) while limiting the accessibility of related but competing words (e.g., Cathedra) that were not practiced (Anderson & Hulbert, 2021; see also Bajo et al., 2021). Finally, participants performed the RAT in which some of the problems could be solved with items that had formed part of the SR stage (e.g., Church-Enormous-Monument, with Cathedra as the solution). The RAT also included problems whose solutions were completely new (they had never been presented during the experiment). The results showed that participants' priming effect (with strong semantic associations only) was the best predictor of performance on the RAT, such that more semantic priming was associated with better creative performance. Importantly, the second best predictor of RAT performance was the participants' inhibitory control as measured by the relative impairment in producing solutions that were competitors during the selective retrieval phase. As noted above, this retrieval-induced impairment (retrieval-induced forgetting, RIF, in the episodic memory literature) has been attributed to inhibitory control processes that downregulate the activation of competing information to overcome interference during selective retrieval (see Anderson & Hulbert, 2021 and Bajo et al., 2021). As a result, successful activation of former competitors during subsequent RAT problems solving became more difficult, and these competitors are significantly less produced as solutions (for related findings in decision making and analogical reasoning see Iglesias-Parro & Gómez-Ariza, 2006, and Valle et al., 2019; 2020a; 2020b, respectively). Interestingly, Lezama et al. found that individual differences in retrieval-induced impairment showed to be associated with RAT performance, such that better inhibitory control predicted enhanced performance on the RAT. Thus, the results of this study by Lezama et al. (2023) support the idea that both semantic associative processes and inhibitory control play significant roles in creativity.

Semantic processes and inhibitory control have been associated with different neural networks. Thus, although semantic cognition requires multiple processes and brain systems, the anterior temporal lobe (ATL) is usually considered a core region for semantic processing (Chen et al., 2016; Lambon Ralph et al., 2017). Specifically, the ATL is a highly interconnected area that plays a critical role in the creation and maintenance of complex semantic representations (Bonner & Price, 2013; Díez et al., 2017; Lambon

Ralph, 2014). Moreover, the ATL is thought to serve as an integration hub responsible for binding modality-specific information from distributed cortices to create amodal conceptual representations (Farahibozorg et al., 2022; Lambon Ralph, 2014; Snowden et al., 2018; Zhao et al., 2017). Importantly, while a number of findings seem to support the bilateral involvement of the ATL as a semantic integration hub (Lambon Ralph et al., 2017), some lines of evidence suggest a functional asymmetry, indicating that the role of the left ATL is more evident when lexical-semantic knowledge is concerned (Alonso et al., 2021; Gainotti, 2012; Mion et al., 2010). Interestingly, some studies have linked the activity in the left ATL with the exploration of conceptual structures stored in memory to generate creative ideas (e. g., Abraham et al., 2012; Abraham et al., 2018; Aihara et al., 2017; Chi & Snyder, 2011, 2012).

Executive control processes thought to contribute to the production of creative ideas have been associated with prefrontal regions such as the inferior frontal gyrus (IFG) and the dorsolateral prefrontal cortex (DLPFC) (Becker et al., 2020; Benedek et al., 2014; Beaty et al., 2017; Cassotti et al., 2016). These areas are thought to be involved in the implementation of top-down control over different cortical and subcortical regions, depending on the specific task being performed (Beaty et al., 2015; Anderson & Hulbert, 2021). For example, the downregulation of interfering information during selective retrieval has been shown to be associated with the right dorsolateral and ventrolateral prefrontal cortices (Kuhl et al., 2007; Stramaccia et al., 2017; Valle et al., 2020a; Wimber et al., 2015). Interestingly, the IFG and DLPFC have also been proposed to play a role in the regulation of semantic processing and access to meaning (Green et al., 2017; Noonan et al., 2010; Sela et al., 2012). Thus, for example, Bendetowicz et al. (2018) observed that patients with brain damage in right prefrontal regions were less creative because they relied on more common links when generating semantic associations in the RAT. Overall, the lateral prefrontal cortex seems to be particularly involved in interference control and, in the case of creativity, in gaining accessibility to original ideas by inhibiting dominant but non-original ones and orienting the semantic search towards task-appropriate semantic knowledge (Benedek & Fink 2019; see Chrysikou, 2019, for a review; Öllinger et al., 2008).

Despite the evidence for a role of semantic processes and inhibitory control in creative performance and their association with activity in temporal and prefrontal regions, to our knowledge no previous study has examined the contributions of both processes in creativity tasks. Therefore, the aim of the present research was to dissociate semantic and inhibitory control processes by using transcranial direct current stimulation (tDCS) to modulate activity in the left ATL (semantic processing/integration) and the right DLPFC (inhibitory control) during creative thinking. TDCS usually involves the delivery of a constant weak electrical current (usually 1-2 mA) typically applied through surface electrodes placed on the participant's scalp over a region of interest. The current flows from anode to cathode over a period of time (usually 10-20 min) and has the potential to modulate cortical excitability (Nitsche & Paulus, 2000) and change brain activity beyond the stimulated area (i.e., functional connectivity within brain networks, Kim et al., 2021). Therefore, tDCS is considered a valuable technique for understanding the involvement of brain areas (and networks) in motor and cognitive functions (Filmer et al., 2014; Bestmann et al., 2015; Fertonani & Miniussi, 2017).

Some studies have already explored the role of the ATL during creative problem solving, particularly in relation to insight, but with mixed results (Aihara et al., 2017; Chi & Snyder, 2011, 2012; Ruggiero et al., 2018). Chi and Snyder (2011, 2012) showed that cathodal tDCS delivered over the left ATL (while anodal tDCS was delivered over the right ATL) reduced participants' susceptibility to functional fixation induced by prior exposure while completing insight problems. In contrast, Aihara et al. (2017) found no evidence that anodal tDCS over the right ATL (with two different electrode montages) influenced performance in creative tasks (matchsticks arithmetic problems and RAT). More recently, Ruggiero et al., (2018) observed that anodal stimulation of the left ATL (coupled with cathodal tDCS of the right ATL) reduced response times in the RAT relative to sham, but this effect did not reach statistical significance in accuracy (note that the sample size in this study was very small: n = 7). In few words, because these studies varied in sample sizes, type of tasks, tDCS protocols and electrode montages, it is still difficult to interpret the effects of tDCS over ATL when solving creative problems.

Regarding the role of the DLPFC in creativity, there seems to be a general consensus on the predominant role of the left DLPFC relative to the homologous region in the right hemisphere, even when the available evidence is also mixed. Cerruti and Schlaug (2009) showed that anodal stimulation over the left DLPFC improved RAT resolution compared to cathodal or sham stimulation, whereas tDCS delivered over the right DLPFC did not change RAT performance (see Zmigrod et al. 2015; Exp. 1 for similar results). More recently, however, Li et al. (2022) observed that, compared with sham stimulation, anodal left/cathodal right tDCS improved the originality of responses in the Alternate Uses Task (AUT) but had no effect on performance in the RAT (for a similar finding see Xiang et al., 2021), which might suggest that divergent thinking may be more easily modulated by tDCS over the DLPFC than convergent thinking.

In summary, previous work has demonstrated the importance of semantic and inhibitory processes in creative problem solving. However, causal evidence for the involvement of anterior temporal and lateral prefrontal areas in RAT problem solving remains to be elucidated. With the aim of clarifying and dissociating the role of the (1) left ATL in semantic integration during creative problem solving (Experiment 1) and (2) the right DLPFC in the downregulation of interfering memory representations that could potentially contribute to creative RAT problem solving (Experiment 2), we report two tDCS experiments using the SR-RAT procedure used by Gómez-Ariza et al. (2017). In this procedure, participants initially studied a list of items consisting of orthography-based categories pairs (e.g.: CA-Canary, CA-Cathedra). In the following phase, they had to repeatedly recall half of the items from only half of the previously presented categories (e.g.: CA-Can_). Finally, they were engaged in solving RAT problems, wherein some of the solutions were words presented in the previous phases, and the rest were entirely new words. The advantage of this behavioral procedure is that it provides indices to assess the relative role of semantic processing (from hits in RAT problems whose solution is a new word) and memory inhibition (from hits in RAT problems whose solutions were competitors during selective retrieval). Although both, semantic processing and inhibitory control, should operate in the search for a RAT solution, in the SR-RAT procedure some RAT problems have a potential solution that has been previously studied and inhibited and, therefore, trying to solve such problems has a strong episodic component. In contrast, RAT problems with new solutions would more probably reflect the result of semantic processing (semantic integration over the presented word triplet to arrive at correct solution). Hence, in the present experiments, the index of creativity (assumed to be more dependent on semantic activation/integration) was the percentage of correct responses to problems whose solution had not been presented previously (new problems). As in previous related studies (see Bajo et al., 2021), inhibitory control was operationalized as the difference between responses to problems that could be solved with competitors and responses to problems that could be solved with studied only items (retrieval-induced impairment; see Bajo et al., 2021).

Importantly, the processes targeted by tDCS in each of the experiments are thought to operate in different time windows. Associative and integration processes are thought to play a role during creative generation (i.e., during RAT problems solving) (Benedek et al., 2023), whereas inhibitory control is thought to operate during retrieval (Bajo et al., 2021). Thus, in Experiment 1 tDCS was applied before the target process (semantic integration) is thought to play its role. This specific timing was chosen based on the results of Díez et al. (2017; see also Boggio et al., 2009), who showed that applying anodal tDCS over the left ATL during the encoding phase of a DRM paradigm generated a reduction in semantically based memory distortions (a behavioral effect thought to depend on the left ATL and its role as an integration hub). However, in Experiment 2, tDCS was intended to hamper inhibitory control of competing memories which could subsequently be solutions in the RAT phase, while leaving semantic integration unaffected. Importantly, previous tDCS studies have shown that cathodal stimulation over the right DLPFC during selective retrieval disrupts inhibitory control of competitors (Stramaccia et al., 2017; Valle et al., 2020b). Hence, in Experiment 2, the tDCS protocol was based on studies showing successful disruption of inhibitory control of competing memories.

In both experiments the potential effects of tDCS were assessed using behavioral and electroencephalography (EEG) measures. In Experiment 1, anodal tDCS over this region was expected to reduce the number of responses to new problems compared to sham stimulation. In Experiment 2, it was predicted that cathodal tDCS over the right DLPFC would specifically increase the production of competitor solutions during selective retrieval. Because previous studies have shown that it disrupts inhibitory control over competing memories (e.g., Valle et al., 2020a), it was expected that former competitors would be more accessible as solutions in the real tDCS group than they would be in the sham group, in which inhibition was expected to act on competitors during selective retrieval. For EEG, resting-state (RS) brain activity was recorded before and after stimulation. Previous studies of RS-EEG and creativity tasks have focused on resolution style (insight/analysis) rather than on how different band frequencies relate to mean performance, and have yielded mixed results using different creativity tasks (Erickson et al., 2018; Kounios et al., 2008; Wu et al., 2014). To the best of our knowledge, only one previous study considered pre-post EEG recordings when tDCS was delivered over bilateral DLPFC during RAT performance (Hertenstein et al., 2019). Although this study found an increase in beta-band power after stimulation, tDCS did not affect performance, nor was beta power associated with creative responses. In the present experiments, RS-EEG was recorded to examine whether there were tDCS-induced changes in power at different frequency bands, as well as possible associations between this activity and RAT performance (e.g., Hertenstein et al., 2019).

Experiment 1

The main goal of Experiment 1 was to determine whether applying anodal tDCS over the left ATL would modulate creative responses in the RAT. Because RAT performance has been shown to be sensitive to individual differences in both associative/semantic and inhibitory processes (Lezama et al., 2023), RAT could also be an appropriate task to target the modulation of such processes using tDCS. The ATL is thought to serve as a semantic integration hub of utmost significance in the establishment and maintenance of complex semantic representations (e.g., Bonner & Price, 2013; Lambon Ralph, 2014), which play a relevant role in creativity (Abraham et al., 2018; Aihara et al., 2017). However, previous studies investigating the effect of anodal stimulation of the left ATL on creativity have yielded mixed results (see Chi & Snyder, 2011, 2012; Ruggiero et al., 2018). Thus, the present experiment aimed to shed light on the involvement of the left ATL in associative/integration processes that are thought to contribute to creative problem solving.

The left ATL has been shown to be involved in the formation of semantically-based false memories due to its role as an integration hub within a semantic brain network (Chadwick et al., 2016). Indeed, anodal tDCS over the left ATL has been shown to reduce semantically based memory distortions (e. g., Boggio et al., 2009, Diez et al., 2017). As mentioned, Díez et al. (2017) observed that semantically-induced memory distortions were reduced after anodal but not cathodal tDCS over the lATL, suggesting that anodal stimulation seemed to disrupt the semantic integration process necessary to induce false memories. Thus, in the present experiment, the same tDCS protocol as Díez et al. (2017) was followed because the main goal was to learn whether the impairment of semantic integration by tDCS would selectively affect the ability to solve creativity problems. For this reason, and because RAT scores have recently been shown to positively correlate with semantically induced false recognition (Thakral et al., 2021; see also Dewhurst et al., 2011), it was expected that anodal tDCS, relative to sham tDCS, over the left ATL would impair RAT performance in the present experiment, particularly for problems whose solution had not been presented previously in the experimental session (i.e., new problems). New problems would more clearly involve semantic processes than problems whose solutions had been previously studied, which would necessarily involve episodic memory because they were previously presented (and studied) during the encoding phase. Therefore, we expected that stimulation would be more likely to affect solutions to new problems than solution to studied problems.

On the other hand, it was hypothesized that solutions that were competitors during selective retrieval would be produced less frequently than studied solutions during the RAT phase (i. e., a retrieval-induced impairment in the RAT). Importantly, because tDCS was applied over left the anterior temporal region, which is not directly associated with inhibitory control, no difference in retrieval-induced impairment was expected between real and sham tDCS. In conclusion, in Experiment 1, tDCS should modulate the creativity index but not the inhibitory index.

Method

Participants.

The minimum sample size was determined in advance based on the effect sizes observed in two previous studies (Díez et al., 2017; Gómez-Ariza et al., 2017). Given the similarity of the materials and procedure to those used by Gómez-Ariza et al. (2017), the (large) effect size of the retrieval-induced impairment (inhibition index) observed in their Experiment 2 (d= 1.37) was assumed. The analysis conducted by using G*Power 3.1 (Faul et al., 2009) indicated that a sample size of 18 participants per group was large enough to detect a statistically significant retrieval-induced impairment (power = 0.80%; alpha = 0.05). Additionally, the effect size (false recognition of critical words in associative lists; anode vs. sham; d = -0.85) observed in the tDCS study by Diez et al. (2017), who also stimulated the left ATL, was considered. The corresponding analysis determined that a sample size of 22 participants per group was large enough to detect group differences. Finally, the sample size included 32 participants per group (mean age = 20.3 years; SD = 3.6, females = 44) to complete the counterbalancing conditions. In order to assess the implicitness of the relationship between some of the solutions to the RAT problems and the previous stages wherein they could appear, participants were asked at the end of the experiment to report whether they had noticed this association (i.e., Have you noticed any association or relationship between the memory task and the RAT?). Only participants who reported that they were not aware of the relationship between the two phases or became aware only during the second block of the RAT, were included in the analysis. Thus, at the end of the experimental session, participants were included in the final sample only on the basis of their response. The total sample collected for Experiment 1 was actually 77 participants, but 13 of them were excluded (10 from the real tDCS group and 3 from the sham group) (Table 1 in the Appendix shows the actual sample sizes in both experiments for behavioral and EEG results). All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected vision and reported no history of neurological or psychiatric disorders, migraines, metal implants, head injuries, seizures, epilepsy or active medication (except oral contraceptive pills). Participants were randomly assigned to the stimulation conditions and remained unaware of their specific tDCS group and the main hypotheses until the end of the experimental session. Ethical approval for the study was granted by the Ethics Committee of the University of Granada (code: 84/CEIH/2015). Participants participated in the study in exchange for course credits.

Materials.

The materials were the same as in Gómez-Ariza et al. (2017) and Lezama et al. (2023). The stimuli were 54 words belonging to nine different orthographic categories, with each category containing six words (i.e.: maquillaje, marinero, matanza, madurez, maleta, and manual for the category MA). Additionally, there were two extra categories; of two words each that were used as fillers to minimize primacy and recency effects during the presentation of the material.

Within each category, there were three words of medium-high lexical frequency (range = 34-98, M = 58.7) and three words of medium-low lexical frequency (range = 10-34, M = 20.14). All exemplars were selected from the normative database of Alameda and Cuetos (1995) according to their lexical frequency. Importantly, the selected words adhered the following standards: a) they had no associative or semantic connections with other words in the category; b) they were two to five syllables long; c) each word had a unique third letter.

The medium-high lexical frequency words were counterbalanced across conditions to form: a) competitor items (words presented during the study phase and belonging to the same category as the practiced words during the SR phase, but never retrieved); b) studied items (words presented exclusively during the study phase and belonging to a different category than the practiced words); c) new items (words neither presented during the study phase nor during the SR phase; and belonging to a different lexical category than the practiced words). Similarly, the words with medium-low lexical frequency were counterbalanced to generate: a) practice words during the SR phase (words presented during the study phase and retrieved during the SR phase); b) studied items (words presented only during the study phase, and belonging to a different lexical category than the practiced words); c) new items (words that were neither presented in the study phase nor in the SR phase and that belong to a different lexical category than the practiced words).

Six task versions were created to counterbalance the material across participants. Within each version, three categories (e.g., CA, PE, FA) were both studied and practiced, resulting in competitors and practiced items. Another set of three categories were studied only during the initial phase (e. g., BA, MA, DE), yielding only studied items. The remaining three categories (e. g., DI, RE, TA) were not studied and corresponded to the new solutions. In the RAT phase, the solution of each problem corresponded to one of the 54 exemplars previously described (e.g., Growth-Reflection-Fruit for Maturity). Similar to Gómez-Ariza et al. (2017) and Lezama et al. (2023), the associative strength between the solutions and the words of the RAT problems was controlled (forward/backward associative strength <.20).

Resting-State EEG acquisition and processing.

Two five minutes eyes-closed resting-state EEG recordings were obtained at the beginning and end of the experimental session using a 40-scalp electrode cap (Quick-Cap, Neuroscan, Inc.) using the 10-20 system. The electrical signal was amplified by a Scan NuAmps system (Compumedics Ltd., VIC, Australia). The sampling rate was set to 1000 Hz with an online filter (high pass: 0.5 Hz; low pass: 70 Hz). Impedance of all electrodes was kept below 10 kΩ, and the EEG signal was referenced to the Cz electrode during data acquisition. The preprocessing and analysis procedures followed the methods described in Prat et al. (2016) and Aguerre et al. (2021). Prior to data analyses, a high-pass filter at 1 Hz was applied and the five minutes recording was segmented into second-s epochs with 0.5s overlap. Artifacts were manually removed using Fieldtrip toolbox on Matlab (Oostenveld et al., 2011) through thorough data inspection. Bad channels, with high level of artifacts (always less than 10% of the total) were identified and interpolated from neighboring electrodes using triangulation method. The average log power spectrum was then calculated over the frequency range from 4 Hz until 40 Hz. To do this, the power spectrum of each epoch was calculated using the Fast Fourier Transform, then log-transformed, and finally; the resulting power spectra were averaged over all epochs. To diminish spectral leakage, a Hanning window was applied to each epoch before the Fast Fourier transform. Finally, the mean log power was calculated across theta (4-7.2 Hz), alpha (8-12.5 Hz), beta (13-29.5 Hz), and low gamma (30-40 Hz) frequency bands for each channel and participant in the two recording times.

Transcranial direct current stimulation. TDCS was delivered using a DC Brain Stimulator Plus (NeuroConn, Ilmenau, Germany) via two saline-soaked surface sponge electrodes. Saline solution with a sodium chloride saturation of 0.9% was used (ERN Laboratories, S.A.) In the anodal group (real tDCS), a constant current of 1.5 mA (0.06 mA/cm^2) was delivered for 20 minutes using a 30 s fade-in and fade-out ramp. The anode (5x5 cm) was positioned on FT9 according to the international 10-10 system for EEG electrode placement. FT9 was chosen because it is considered the closest electrode to the left ATL (BA 38) (Acharya et al., 2016; see also Díez et al., 2017). The reference electrode (5x7 cm) was placed on the contralateral deltoid muscle to minimize its effect on the brain. For the sham group, the montage mirrored that of the active group, but the current intensity was reduced to 0.75 mA and lasted 30 seconds, with an eight seconds fade-in and fade-out ramp. Figure 1 depicts the electrode montage and simulated current flow using SimNIBS (4.0.1) software (Thielscher et al., 2015).

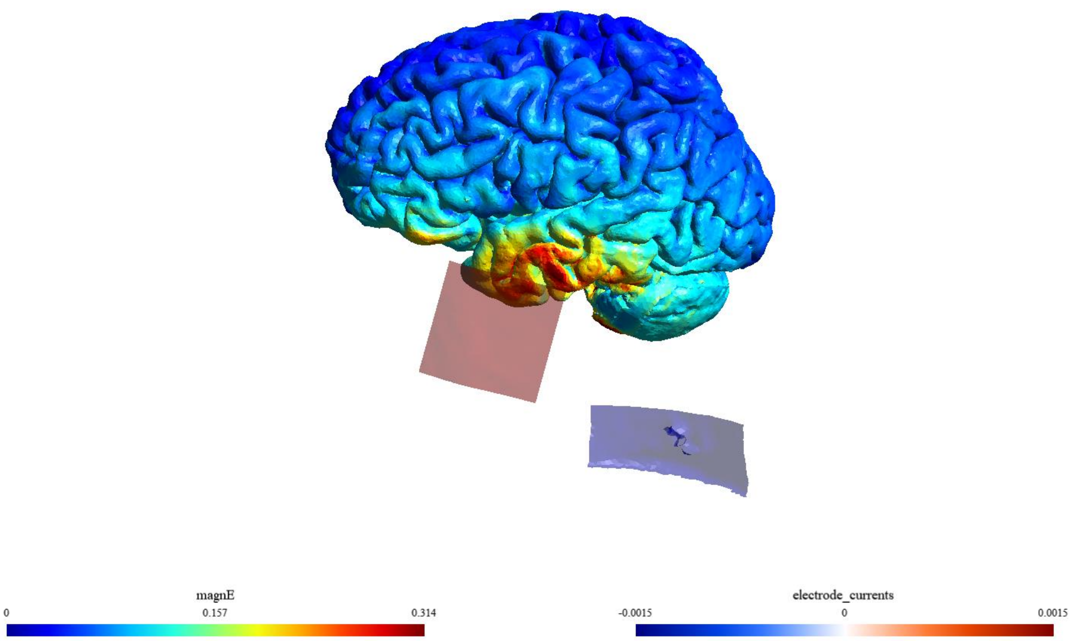

Figure 1. tDCS electrode montage and simulation of the current flow performed using SimNIBS 4.0.1 (Thielscher et al., 2015). The 5x5 cm anode electrode was positioned over the left anterior temporal lobe (FT9). The 7x5 cm cathode electrode was positioned over the contralateral shoulder. The strength of the induced electrical field (magnE) is depicted in V/m and the current generated by each electrode in presented in mA.

As is common in neuromodulation research, participants were asked to remove metal objects from their bodies. Elastic bands were used around the participants' chest and head to prevent displacement of the electrodes in case of movement. Importantly, the stimulator was always manipulated between tasks to disguise the stimulation assignment; and was always out of reach for participants. They could never see the screen of the device (which was covered with paper) or press any buttons.

Procedure.

The experimental procedure was very similar to that used by Gómez-Ariza et al. (2017), albeit with adaptations to include the tDCS and resting EEG recording protocols. The experimental session lasted approximately two and a half hours. Once participants read and signed the written consent, the pre-task resting-state EEG recording began. Participants were instructed to close their eyes, relax, and avoid movement for five minutes. The tDCS electrode montage was then prepared. Figure 2 shows a schematic representation of the experimental procedure.

Participants then performed the adapted SR task followed by the RAT. During the encoding phase, a sequence of orthography-based categories and exemplars pairs (e.g., CA-Canary) was presented for five seconds, with a one-second interval between pairs. Participants were required to memorize each syllable-exemplar pair. The 36 pairs of stimuli were presented twice in random order, with the same two filler categories (FI y LE) always presented at the beginning and end of the list. After the instructions were explained, the tDCS (anodal or sham) started and continued through the study phase (approximately 12 minutes), and the eight minutes distractor task that participants performed after the study. In this task, participants had to circle three different letters (k, w, and z) within a text written in an unfamiliar foreign (Polish) language. Then, in the selective retrieval phase, participants were asked to repeatedly recall half of the items from half of the studied categories. Each trial began with the presentation of a category cue (e.g.: CA) for two seconds, followed by one-second interval during which a three-letter exemplar fragment appeared (e.g.: Can_) for five seconds. Participants were asked to say aloud the unique word from the preceding phase that matched the fragment. Each trial was practiced three times in random blocks of three items, with each category appearing only once. Filler categories were always presented at the beginning and end of each block. Participants then performed another distraction task involving arithmetic operations for five minutes.

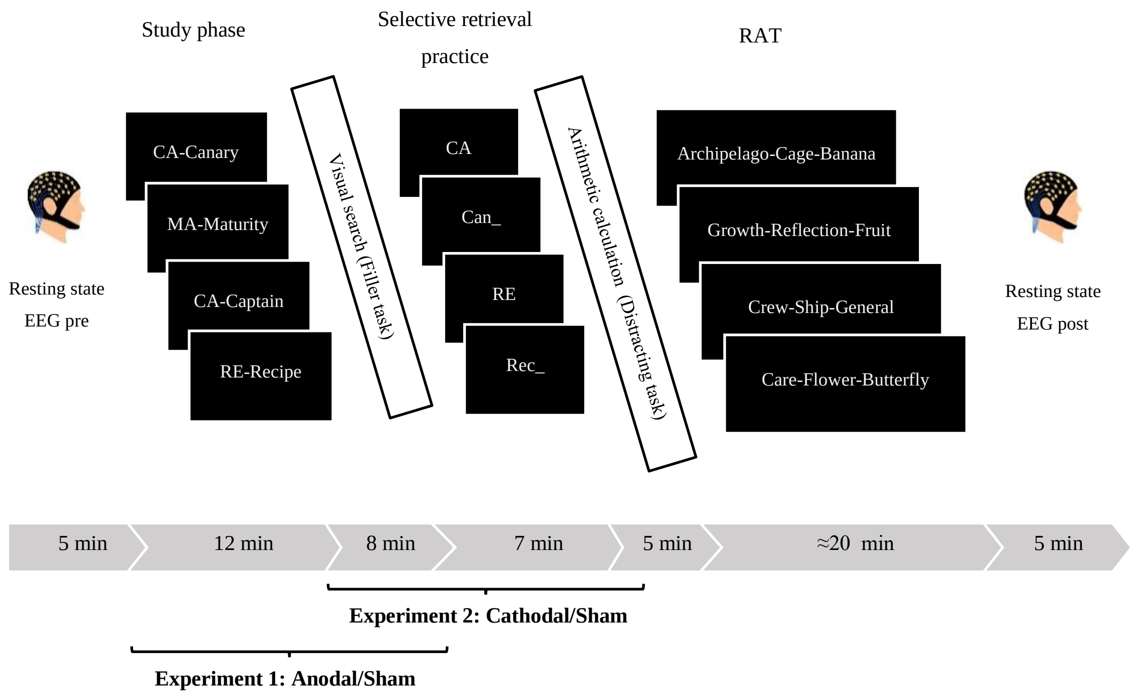

Figure 2. Schematic representation of the experimental procedure. The same procedure was followed in Experiments 1 and 2, except for the tDCS protocol. In Experiment 1, anodal tDCS was applied over the left ATL during the study phase. In Experiment 2, cathodal tDCS was applied over the right DLPFC during the selective retrieval phase. In both cases, real tDCS lasted for 20 minutes.

Finally, participants completed the RAT problems. Participants were told that they had to solve creative problems consisting of three words lacking an apparent association between them. They were instructed to find a fourth word that was related to all three.

Additionally, they were informed that the relationship could be based on context, semantic field, synonymy, descriptions, etc. Before starting the experimental task, two RAT problems were presented to familiarize the participants with the procedure. The 54 problems were divided into two different blocks according to the lexical frequency of the solutions, and presented in a random order within each block. The first block contained problems whose solutions were high-frequency words (i.e., competitors during the SR phase, only-studied words or new solutions). In the second block, problems could be solved with low-lexical frequency words (i.e., targets during SR, only-studied words, and new solutions). Participants had up to one minute to produce a solution to each problem. If participants did not provide an answer, the next problem appeared automatically after one-minute time limit. At the end of the task, a post-task questionnaire was administered to assess participants' awareness of the relationship between encoding/SR and RAT. Before the stimulation began, participants were instructed to inform the experimenter if they felt any discomfort. At the end of the experimental session, participants were asked which tDCS condition they thought they had been assigned to and finally they completed a questionnaire on potential adverse effects of tDCS (Brunoni et al., 2011).

Results

The results of analyses of variance (ANOVAs) on performance in the selective retrieval phase and the RAT are reported below. In all cases, stimulation (real vs. sham) was introduced as a between-groups factor. RAT performance was analyzed considering correct responses to problems with different solution type (new, competitor, studied). Specifically, to examine the effect of tDCS on creativity (without the influence of the selective retrieval manipulation), the focus was on correct responses to new and studied problems (collapsing both blocks of RAT problems). As for the retrieval-induced impairment, it was analyzed by considering correct responses to problems whose solutions were competitors during selective retrieval and correct responses to problems with studied solutions (all presented during the first problem block).

EEG activity was analyzed by considering averaged power in each band frequency (i.e., theta, alpha, beta, and low gamma; see previous section for detailed EEG data processing). A mixed ANOVA with stimulation (real vs. sham) as the between-group factor and recording time (pre-task vs. post-task) as the within-subject variable was performed as well as correlation analyses (Spearman's rho) between pre-task and post-task power. Finally, the differential resting-state activity for each band frequency was obtained (by subtracting the pre-task EEG measurements from the post-task EEG measurements), and correlation analyses (Spearman's rho) between this measure and correct responses to new problems (the only ones modulated by tDCS) were performed for both stimulation groups.

Responses to the adverse effects questionnaire indicated that none of the participants experienced major complaints or discomfort associated with stimulation. Table 2 in the Appendix summarizes the self-reported frequency of effects in both groups and the incidence of correct guessing of group assignment, along with p values for between-groups comparisons.

Behavioral results

Effect of neuromodulation and prior exposure on creative responses. To examine the potential effect of tDCS over the left ATL on creative performance, only responses to problems that could be solved with new solutions (items never presented during the experimental session) and studied solutions (i.e., studied items that were neither targets nor competitors during retrieval practice) were considered. Thus, a 2 (tDCS: Real vs. Sham) x 2 (type of solution: Studied vs. New) mixed ANOVA on correct responses to

RAT problems was conducted. The analysis revealed a main effect of type of solution, $F(2,62) = 29.13$, $p < 0.001$, $\eta^2_p = 0.32$, indicating that participants resolved more RAT problems whose solution had been previously studied (Studied: $M = 44.20$; $SD = 14.70$; New: $M = 34.10$; $SD = 11.20$). There was also a main effect of tDCS, such that participants who received real stimulation ($M = 37.33$; $SD = 10.92$) produced fewer responses than participants in the sham group ($M = 42.55$; $SD = 10.93$; $F(2,62) = 7.59$, $p = 0.008$, $\eta^2_p = 0.10$). More importantly, the interaction reached statistical significance, $F(2,62) = 5.21$, $p = 0.02$, $\eta^2_p = 0.07$. Simple effects analyses revealed that there was no difference between real and sham tDCS when participants solved problems whose solution had been previously studied ($M_{Real}= 42.90$; $SD_{Real} =14.30$; $M_{Sham}= 45.50$; $SD_{Sham}= 15.23$, $F(1,62) < 1$, $\eta^2_p < 0.01$). In contrast, in the case of problems to be solved with unstudied solutions real tDCS led to fewer correct responses ($M = 28.50$; $SD = 7.82$) than Sham tDCS ($M = 39.64$; $SD = 11.33$), $F(1,62) = 21.08$, $p < 0.001$, $\eta^2_p = 0.25$ (see Figure 3).

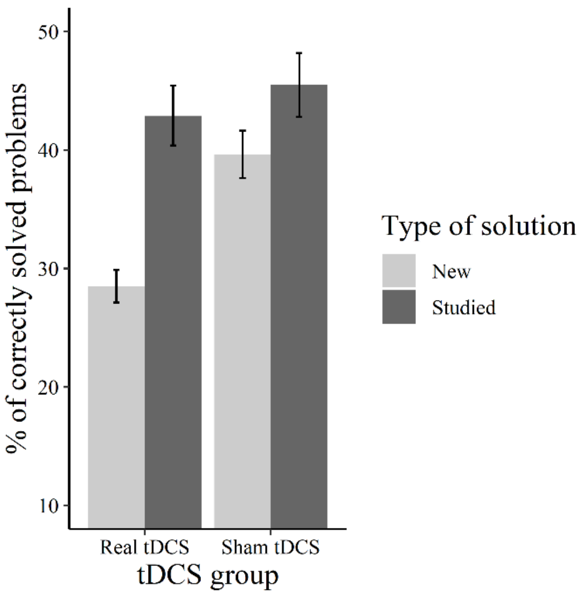

Figure 3. RAT performance in Experiment 1 as a function of stimulation and type of solution. Studied: Problems whose solution was studied in the first phase of the experimental session but was not target

nor competitor during retrieval practice. New: Problems whose solution was never presented in the experimental session. Error bars represent standard errors of the mean.

Selective retrieval and retrieval-induced impairment in RAT performance. The overall mean percentage of successful recall during the SR phase was 89.45 (SD = 12.01). Performance was not significantly different between the two stimulation groups (M_{Sham} = 89.50, SD_{Sham} = 12.02; M_{Real} = 89.41; SD_{Real} = 12.20; $F(1,62) < 1$, $\eta^2_p < 1$). For the RAT phase, the overall mean percentage of correctly solved problems was 39.94 (SD = 11.20), with the difference between real and sham groups only approaching statistical significance (M_{Sham} = 42.55, SD_{Sham} = 10.93; M_{Real} = 37.33; SD_{Real} = 10.92; $F(1,62) = 3.66$, $p = 0.06$, $\eta^2_p = 0.06$).

To test whether tDCS modulated the retrieval-induced impairment in the RAT (which was not expected in Experiment 1), a 2 (tDCS: Real vs. Sham) x 2 (type of solution: Competitors vs. Studied) mixed ANOVA was performed. It should be noted that for this analysis and following the procedure from previous studies on retrieval-induced impairments (e.g., Bajo et al., 2006; Gómez-Ariza et al., 2012; Gómez-Ariza et al., 2017; Valle et al., 2020a; Weller et al., 2013), the studied solutions considered belonged to the high-medium lexical frequency items. The results revealed a main effect of solution type indicating that competitor items (those that were competitors during the SR phase; M = 33.20; SD = 17.70) were produced less as solutions than studied items (M = 40.50; SD = 17.64), $F(2,62) = 7.86$, $p = 0.007$, $\eta^2_p = 0.11$, (see Figure 4: see also Table 3 in the Appendix for descriptive statistics). However, there was no main effect of tDCS, $F(2,62) < 1$, $\eta^2_p = 0.00$ or interaction, $F(2,62) < 1$, $\eta^2_p = 0.014$. This pattern of results indicates that tDCS over the left ATL did not modulate retrieval-induced impairment.

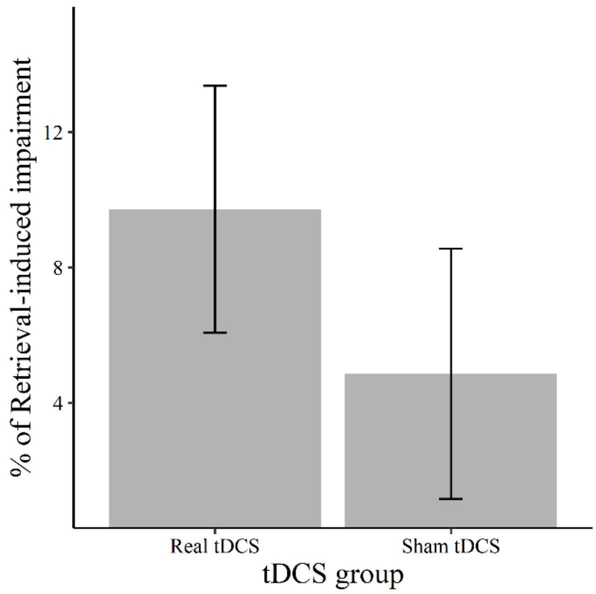

Figure 4. Retrieval-induced impairment (percentage of problems correctly solved with competitors subtracted from the percentage of problems correctly solved with studied only solutions) as a function of stimulation group. Error bars represent standard errors of the mean.

EEG results

Effects of neuromodulation in resting-state EEG. Due to technical failures, data from three participants (two real and one sham) were missing from the pre-task recording and further three from the post-task one (all from the sham group). To determine whether there were group differences in resting-state brain activity, a 2 (tDCS: Real vs. Sham) x 2 (recording time: pre-task vs. post-task) mixed ANOVA on mean power for each frequency band was conducted considering the following clusters from the 40 channels: anterior-frontal (FP1, FP2), left-frontal (F3, F7, FC3) right-frontal (F4, F8, FC4), left-parietal (P3, P7) right-parietal (P4, P8) left-temporal (FT7, FT9, T7) right-temporal (FT8, FT10, T8) and occipital (O1, OZ, O2) and the whole set of electrodes). No statistically significant effects were found (all *Fs* <1; *ps* > 0.45). Descriptive statistics in each band frequency of the whole set of electrodes are summarized in Table 1.

Table 1. Means (and standard deviations) of power in each band frequency as a function of tDCS and recording time in Experiment 1.

tDCS group	Band frequency	Pre	Post
Sham tDCS	Theta	2.39 (3.68)	2.55 (2.26)
	Alpha	2.61 (3.76)	2.86 (2.26)
	Beta	2.24 (3.34)	2.34 (1.87)
	Gamma	1.83 (3.06)	1.81 (1.58)
Real tDCS	Theta	2.42 (2.14)	2.62 (1.61)
	Alpha	2.68 (2.15)	2.94 (1.58)
	Beta	2.33 (1.85)	2.52 (1.33)
	Gamma	1.95 (1.65)	2.04 (1.16)

Pre and post EEG activity was then correlated separately for each group to examine the consistency of power. For the sham group, the analyses showed positive and reliable associations across all frequency bands. For the real tDCS group, however, there were statistically significant correlations for alpha, beta and gamma, but not theta [see Table 2; see and also Figure 1(a) in the Appendix], suggesting that real tDCS induced changes in theta band power that were not present in the sham group.

Table 2. Pre-post correlations in power as a function of tDCS and band frequency in Experiment 1.

Band frequency	Sham tDCS	Real tDCS
	Spearman ‘s rho (ρ)	Spearman ‘s rho (ρ)
Theta	0.59**	0.25
Alpha	0.53**	0.46**
Beta	0.55**	0.51**
Gamma	0.45*	0.39*

*$p < 0.05$, ** $p < 0.01$

Differential EEG resting-state activity and performance in new problems. To determine whether performance on problems with new solutions, the problems on which tDCS was shown to have a behavioral effect, was associated with resting-state EEG activity, post-pre differences in power for each frequency band were correlated with correct responses in each tDCS group. Spearman’s correlation analyses revealed a different pattern of associations in each group. In the sham group, the number of correct responses was positively associated with the change in theta band ($r = 0.42$; $p < 0.05$; see Figure 5). That is, the greater the change in resting power from pre to post, the higher the rate of correct responses to problems. In the real stimulation group, however, no reliable correlation emerged ($\rho s < 0.1$, $ps > 0.43$).

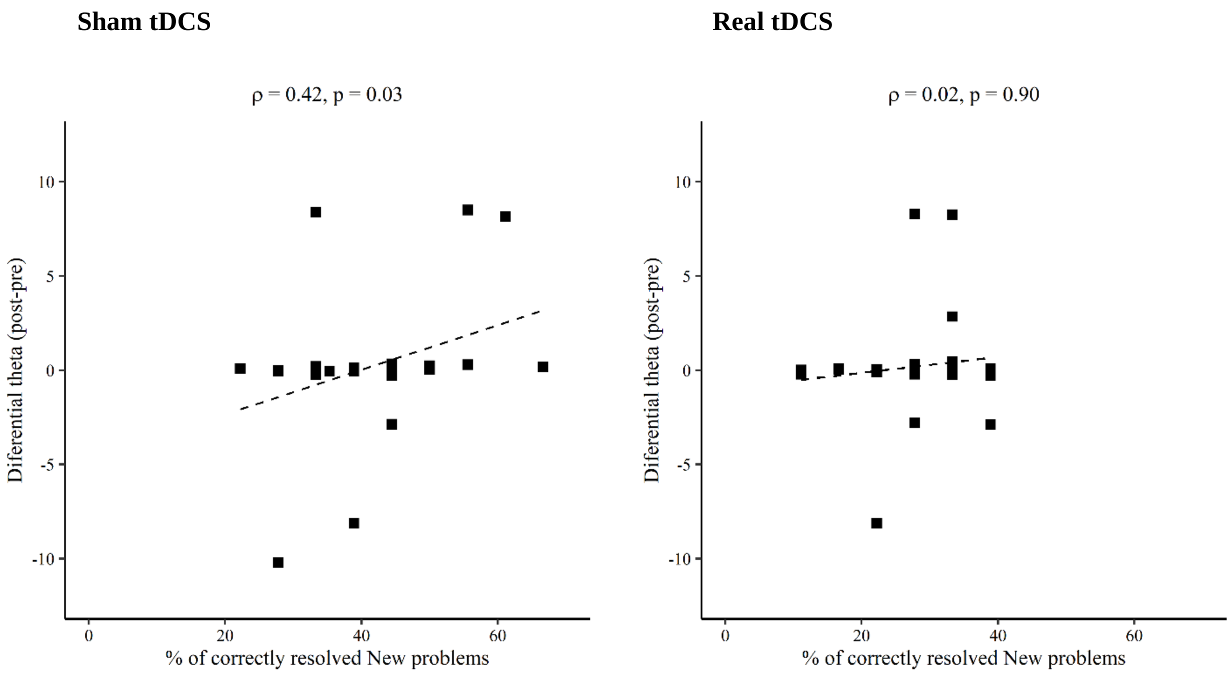

Figure 5. Scatterplots of the relationship between differential theta and creative performance (correct responses to problems with new solution) in both tDCS groups in experiment 1. Spearman's coefficients and associated p-values are also shown.

Interim discussion

Experiment 1 aimed to test the implication of the left ATL in solving RAT problems using anodal tDCS, which has previously been shown to be effective in disrupting performance on cognitive tasks that also require the contribution of the ATL as a semantic integration hub (Abraham et al., 2018; Díez et al., 2017; Ruggiero et al., 2018). Consistent with such an implication, participants in the real tDCS group exhibited a reduced ability to accurately solve RAT problems compared to their sham counterparts. Importantly, this behavioral effect was uniquely observed in the (new) problems whose solutions were words that were never presented in the experimental session, mimicking the standard problems usually included in the RAT. It should be noted that these solutions were unaffected by prior exposure during the study phase or by inhibitory control during selective retrieval, and are therefore the most appropriate index to assess the potential effect of tDCS on the left ATL and its contribution to creative problem solving.

Importantly, no other performance differences between the stimulation groups emerged. Selective retrieval success was comparable in both groups. Similarly, performance in the remaining problem conditions (to be solved with competitors and studied items) was comparable in both tDCS groups, replicating previous findings in the literature on selective retrieval and its consequences for decision making and problem solving (Gómez-Ariza et al., 2017; Iglesias-Parro & Gómez-Ariza, 2006; Lechuga et al., 2012; Valle et al., 2019, 2020b). This strongly supports the notion that the left ATL is not involved in the downregulation of competing responses. Previous exposure to some of the (studied) items prevented anodal tDCS from interfering with their generation as solutions. Thus, it is possible that increased activation and accessibility of these items minimized their dependence on brain regions (such as ATL) involved in complex semantic integration. If so, these solutions would be less susceptible to the disruption of neural activity in the left ATL by tDCS.

Of relevance, tDCS did influence the pre-post correlation in theta power. Thus, while the sham group showed reliable correlations in power across frequency bands between the two sessions of RS-EEG recording, this was not the case for theta band after real tDCS. Interestingly, it was only in the sham group that differential theta power (post-pre differential activity) was associated with improved performance on the new RAT problems, suggesting that the behavioral effect of anodal tDCS might be mediated by changes in the theta band.

Experiment 2

This experiment involved the same procedure as Experiment 1 except for the tDCS protocol. The main goal was to examine whether inhibitory control (which has been associated with activity in the right DLPFC) is involved in modulating the accessibility of relevant memory representations for the creativity task. In this case, the hypothesis was based on findings from previous tDCS studies using the selective retrieval paradigm (Stramaccia et al., 2017; Valle et al., 2020a). These studies showed that cathodal tDCS over the right DLPFC during the SR phase disrupts the downregulation of competing memories, making them as accessible as baseline memories in subsequent memory or problem-solving tests. Thus, compared to the sham condition, cathodal tDCS during selective retrieval was expected to disrupt inhibitory control over competitors' memories (those of items that were not to be retrieved but were related to targets during the SR phase) (Penolazzi et al., 2014; Valle et al., 2020a), as this process is thought to occur during selective retrieval (Anderson & Hulbert, 2021). Therefore, and closely following the tDCS protocol used by Valle et al. (2020a), it was expected that real tDCS, but not sham tDCS, would prevent the retrieval-induced impairment from manifesting in the RAT. In other words, it was predicted that cathodal tDCS would cause participants to produce competitors and studied solutions similarly. In contrast, tDCS was expected to have null or a smaller effect over new problems because the RAT problems employed in the present studies were not created to be solved under conditions of high competition. In addition, previous studies have shown changes in RAT performance (i.e., improvements) after tDCS of the left DLPFC but not of the right DLPFC (Cerruti & Schlaug 2009; Zmigrod et al., 2015).

Method

Participants.

The required sample size for this study was calculated using G*Power 3.1 (Faul et al., 2009) and assuming a medium effect size (partial squared eta = 0.06[1]) of a 2 x 2 interaction in a mixed ANOVA (tDCS group x type of items on which retrieval-induced impairment was calculated). A total sample of 34 participants was sufficient to detect a statistically significant interaction (power = 0.80%; alpha = 0.05). The final collected sample consisted of 40 participants who met the same requirements as in Experiment 1 and were randomly assigned to the stimulation groups. As in the previous experiment, participants were completely blind to their assignment and to the hypothesis of the study and agreed to participate in exchange of course credits or economical compensation (15€).

Materials.

The same as in Experiment 1.

Resting-State EEG acquisition and processing.

The EEG recording was similar to Experiment 1 except that a 32-scalp electrodes cap (Quick-Cap Neo net, Neuroscan, Inc.) was used. The electrical signal was amplified by a Grael system (Compumedics Ltd., VIC, Australia). The sampling rate was set to 2050 Hz with an online filter (high pass: 0.5 Hz; low pass: 70 Hz). The raw signal was

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[1] In a related study in which cathodal tDCS was shown to eliminate retrieval-induced impairment in analogy problem solving (Valle et al., 2020a), the effect size of the interaction was large (partial squared eta = 0.16). For the present study, however, a more conservative approach was preferred, and we predicted only a medium effect size even though it would demand a larger sample size.

downsampled to 1000 Hz, and the same protocol as in Experiment 1 was followed to process and analyze the data.

Transcranial direct current stimulation.

The stimulation protocol was identical to that used in Experiment 1, except for the timing of current application (the SR phase rather than the encoding phase), the site of stimulation and the polarity of the electrode of interest. As in Valle et al. (2020a), the cathodal electrode was placed over the right DLPFC (BA 46/9) centered on F4 according to the international 10-10 system for EEG electrode placement. The reference electrode was placed on the contralateral deltoid muscle. Figure 6 depicts the electrode montage and simulated current flow using SimNIBS (4.0.1) software (Thielscher et al., 2015).

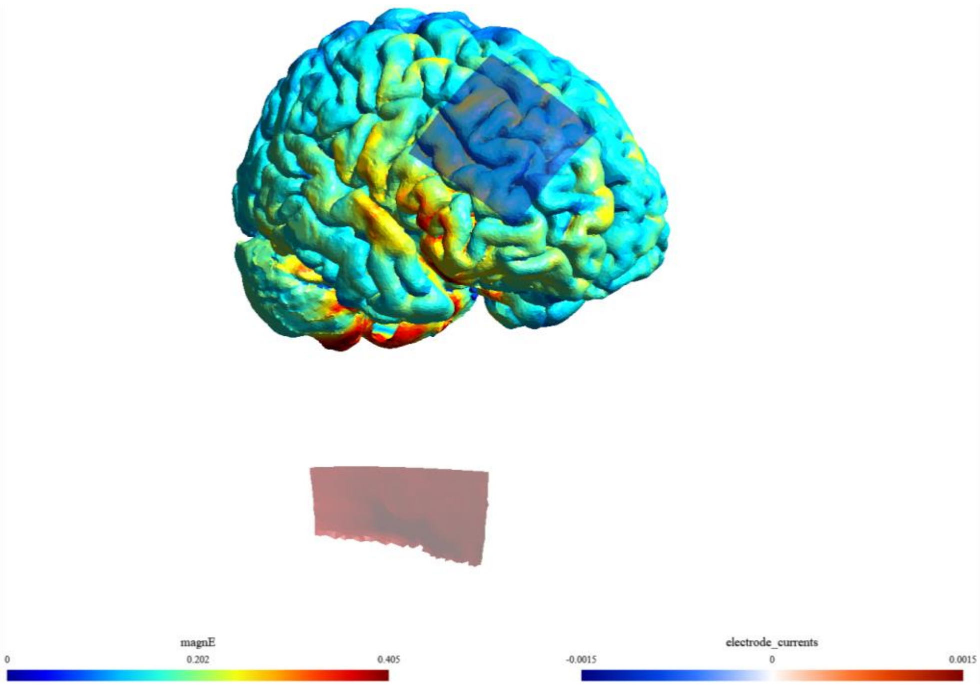

Figure 6. tDCS electrode montage and simulation of the current flow performed using SimNIBS 4.0.1 (Thielscher et al., 2015). The 5x5 cm anode electrode was positioned over the right dorsolateral prefrontal cortex (F4). The 7x5 cm cathode electrode was localized over the contralateral shoulder. The strength of the induced electrical field (magnE) is depicted in V/m and the current generated by each electrode in presented in mA.

Procedure

The experimental procedure was the same as in the previous experiment and also lasted approximately two hours and a half (see Figure 2, Experiment 2, for a schematic representation of the procedure). Since the goal of tDCS was to disrupt inhibitory control-related activity in the right prefrontal cortex, current delivery (either sham or real) was started during the first distracting task, after the study phase that lasted eight minutes, continued throughout the SR phase (seven minutes) and was finished during the second distracting task. As in Valle et al. (2020a), the RAT problems whose solution was a practiced word were not presented in order to minimize participants' awareness of the associations between experimental tasks.

Results

The analytical approach to the data of the present experiment was identical to that of Experiment 1. The adverse effects questionnaire indicated that participants did not experience any major discomfort related to the stimulation, nor were they able to guess their stimulation condition (see Table 4 in the Appendix).

Behavioral results

Effect of neuromodulation on creative responses and type of solution. To examine whether tDCS modulated creative performance, a 2 (tDCS: Real vs. Sham) x 2 (type of solution: Studied vs. New) mixed ANOVA was performed on correct responses. The results revealed a main effect of type of item, so that studied items (M = 45.28; SD = 14.54) were produced as solutions more often than new items (M = 33.06; SD = 12.32; See Figure 7). Neither the main effect of tDCS $F(1,38) < 1$, $p = 0.6$, $\eta^2_p < 1$) nor the interaction reached statistical significance $F(1,38) = 3.03$, $p = 0.09$ $\eta^2_p = 0.07$).

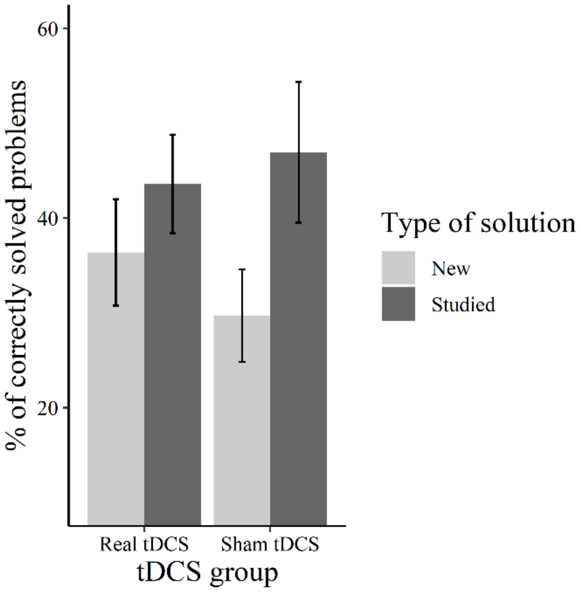

Figure 7. RAT performance in Experiment 2 as a function of stimulation and type of solution. Studied: Problems whose solution was studied in the first phase of the experimental session but was not target nor competitor during retrieval practice. New: Problems whose solution was never presented in the experimental session. Error bars represent standard errors of the mean.

*Selective retrieval and retrieval-induced impairment in RAT performan*ce. A one-way ANOVA indicated that performance during selective retrieval did not differ as a function of stimulation (M_{Sham} = 55.14, SD_{Sham} = 14.92; M_{Real} = 53.51; SD_{Real} = 13.46; $F(1,38) < 1$, $\eta^2_p < 1$).

A 2 (tDCS: Real vs. Sham) x 2 (Type of solution: Studied vs. Competitor) mixed ANOVA on correct responses was conducted to examine the effect of tDCS over the right DLPFC on retrieval-induced impairment in the RAT (see Table 5 in the Appendix for descriptive statistics). A main effect of type of solution was found, $F(2,38) = 4.20$, $p = 0.04$, $\eta^2_p = 0.09$, showing that participants correctly solved more problems whose solution was a previously studied word ($M = 44.17$; $SD = 18.40$) compared to problems whose solution was a competitor during selective retrieval ($M = 34.44$; $SD = 23.84$). The main effect of tDCS was not significant, $F(1, 38) = 1.91$; $p > 0.1$; $\eta^2_p = 0.05$). However, there was a reliable interaction between tDCS and type of solution, $F(2,38) = 8.90$, $p < 0.01$,

η^2_p = 0.19. Follow-up analyses revealed that participants in the sham group exhibited a reliable retrieval-induced impairment such that they solved fewer problems with competitors (*M* = 24.44; *SD* = 18.94) than with studied solutions (*M* = 48.33; *SD* = 17.76); $t(19) = 4.66$; $p < 0.001$; $d = 1.04$). On the contrary, participants in the real tDCS group produced similarly solutions that were competitors (*M* = 44.44; *SD* = 24.45) and solutions that were not (*M* = 40.00; *SD* = 18.52; $t(19) = -0.56$; $p > 0.5$, $d = -0.12$). Figure 8 shows the mean retrieval-induced impairment in each stimulation group.

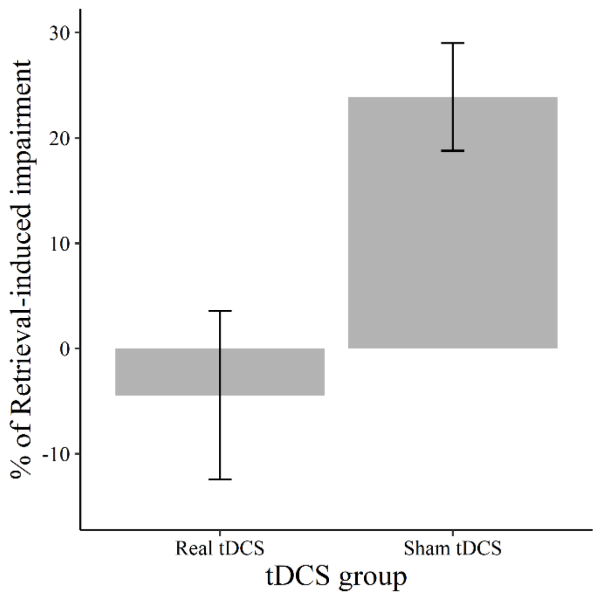

Figure 8. Retrieval-induced impairment (percentage of problems correctly solved with competitors subtracted from the percentage of problems correctly solved with studied only solutions) as a function of stimulation group. Error bars represent standard errors of the mean.

EEG results

Effects of neuromodulation on resting-state EEG. The 2 (tDCS: Real vs. Sham) 2 x (recording time: pre-task vs. post-task) mixed ANOVAs on power for each frequency band indicated that there were no statistically significant differences in any frequency band (all *Fs* < 1; $p > 0.6$). Descriptive statistics are summarized in Table 3. Correlational analyses were performed between pre and post EEG activity in each group. While the sham group showed a positive association for each band frequency between pre and post measurements, the real tDCS group showed significant correlations for theta and beta but not for alpha and gamma [see Table 4, and Figure 2(b) and Figure 2(c) in the Appendix]. This suggests that cathodal tDCS over the right lateral prefrontal cortex specifically induced changes in alpha and gamma power.

Table 3. Means (and standard deviations) of power in each band frequency as a function of tDCS and recording moment in Experiment 2.

tDCS group	Band frequency	Pre	Post
Sham tDCS	Theta	1.98 (2.62)	1.62 (3.04)
	Alpha	2.25 (2.60)	1.94 (3.00
	Beta	1.87 (2.18)	1.53 (2.50)
	Gamma	1.54 (1.97)	1.21 (2.24)
Real tDCS	Theta	1.98 (2.62)	1.92 (2.67)
	Alpha	2.33 (2.60)	2.43 (2.73)
	Beta	1.82 (2.11)	1.81 (2.15)
	Gamma	1.55 (1.90)	1.46 (1.93)

Table 4. Correlations between pre-task and post-task power as a function of group and band frequency in Experiment 2.

Band frequency	Sham tDCS	Real tDCS
	Spearman 's rho (ρ)	Spearman 's rho (ρ)
Theta	0.47*	0.65**
Alpha	0.53*	0.18
Beta	0.59**	0.55**
Gamma	0.51*	0.31

*p < 0.05, ** p < 0.01

Differential EEG resting-state activity and performance in creative problems. It was also examined whether resting-state EEG activity was associated with performance during problem solving. Specifically, the focus was on the behavioral index that was affected by tDCS (retrieval-induced impairment). Thus, the post-pre difference in power for each frequency band across participants was correlated with their retrieval-induced impairment. The sham group showed a correlation between change in alpha and retrieval-induced impairment that only approached statistical significance (ρ = -0.42, p = 0.06), such that the smaller the change in alpha from pre to post, the greater the impairment participants showed in producing competitors as solutions. Analyses in the real tDCS group revealed no associations between differential power in any frequency band and the magnitude of retrieval-induced impairment (all *ps* > 0.5; see Table 5).

Table 5. Correlation coefficients (Spearman‘s rho) between differential power (post-pre) and retrieval-induced impairment as a function of frequency band and group in Experiment 2.

Band frequencies	**Sham tDCS**	**Real tDCS**
Theta	-0.23	-0.02
Alpha	-0.42*	0.10
Beta	-0.38	0.12
Gamma	-0.25	0.16

*p = 0.06

Interim discussion

The goal of the present experiment was to determine whether disruption of inhibitory control (during selective retrieval) by cathodal tDCS over the right prefrontal cortex alters performance in the RAT. Specifically, it was expected that real tDCS would increase correct responses to problems that could be solved with solutions that were competitors during the SR stage, since the disruption of inhibitory control should make competitors comparable to only-studied items in accessibility and production as solutions (thus diminishing the otherwise expected retrieval-induced impairment in the RAT). The results clearly supported this expectation. While a reliable retrieval-induced impairment was present in the sham group, no such effect was evident in the real tDCS group. No other tDCS-related differences in performance were observed (importantly, problems with new and studied solutions were solved similarly in both stimulation groups).

Resting-state EEG analyses also revealed a tDCS-induced change in power in two frequency bands. All pre-post correlations were statistically significant in the sham group, suggesting stability across participants between the two recording sessions. In addition, changes in alpha band marginally predicted the relative production of competitors as solutions. In the real tDCS group, however, the consistency of alpha and gamma power was altered and no association between differential power and retrieval-induced impairment was observed.

General discussion

Although previous neuromodulation studies have already investigated the implication of temporal and prefrontal regions in creative thinking, the results regarding the left ATL and the right DLPFC remained inconclusive (Koizumi et al., 2020; for a review see Weinberger et al., 2017). Hence, the main goal of the present study was to test the hypotheses that 1) the left ATL plays a role in the production of creative responses requiring semantic integration (Experiment 1), and 2) the right lateral prefrontal cortex is involved in the inhibition of competing information, which might subsequently contribute to the production of creative responses (Experiment 2). Both studies worked as reciprocal control experiments to examine if tDCS over each region of interest differentially modulates different neural networks and cognitive processes associated with creative thinking. In the present experiments, participants performed an adapted selective retrieval task followed by a RAT containing problems that could be solved with studied (some of which also became competitors during selective retrieval) and new words. This is a procedure that allows the dissociation between semantic processing (from hits to RAT problems whose solutions are new words) and memory inhibition (from hits to RAT problems whose solutions were competitors during selective retrieval). Although solving

RAT problems involves both semantic processing and inhibition (e.g., Lezama et al., 2023), in the SR-RAT procedure semantic processing is better captured by solutions to new problems since they are not primed by episodic processing during study and/or selective retrieval. In contrast, the production of solutions that were competitors during selective retrieval is a good marker of memory inhibition, since their reduced presence in responses to RAT problems would index the consequences of inhibitory control.

Thus, in Experiment 1, it was expected anodal tDCS over the left ATL to hamper RAT problems solving, particularly for problems whose solutions were not previously presented in the context of the experiment. Additionally, it was hypothesized that the impairment typically observed after selective retrieval (Gómez-Ariza et al., 2017; Lezama et al., 2023) would not be affected by stimulation of the left ATL. In Experiment 2 the hypothesis was that cathodal tDCS of the right DLPFC applied during selective retrieval would interfere with the inhibitory mechanism acting on competing items, preventing them from being downregulated but consequently making them more accessible as solutions during the RAT phase. Thus, less retrieval-induced impairment was expected compared to the sham condition. Finally, real tDCS was expected to modulate resting-state EEG in both experiments.

The pattern of results from Experiment 1 indicated that real tDCS led participants to produce fewer responses to new RAT problems than sham tDCS. Solving new RAT problems requires access to information that is semantically related to the cue words in the problem as well as the combination of this information to generate candidate solution ideas (Smith et al., 2013). Hence, the main finding of Experiment 1 suggests that the left ATL, as an integration hub within the semantic memory network (Bonner & Price, 2013; Lambon Ralph, 2014), plays a relevant role in the generation of possible solutions to RAT problems which was disrupted by anodal tDCS. This finding is consistent with results from neuroimaging studies that have identified enhanced activation of the left ATL linked to semantic processing during creative tasks such as the AUT and RAT (Abraham et al., 2012, Abraham et al., 2018; Tik et al., 2018). Interestingly, the finding also fits with theoretical frameworks that point to the left ATL as a hub specialized in binding information from different brain areas to form coherent conceptual representations (Lambon Ralph, 2014). The left ATL seems to play a particularly significant role in the processing of verbal information (Jefferies, 2013; Díez et al., 2017) and in situations where complex conceptual constructions are required (Baron & Osherson, 2011).

However, this main finding differs from the results of previous studies in which tDCS was delivered over the ATL. In two studies, Chi and Snyder (2011, 2012) found that bilateral (right anodal) tDCS increased participants' creative performance that relied heavily on visuospatial information (matchsticks and 9-dot problems). A similar bicephalic montage was used in the study by Aihara et al. (2017), wherein matchsticks and RAT problems were used to examine the effect of tDCS on creativity. No effect, however, was observed, in contrast to the present finding. These differences are likely due to methodological factors. First, there is some evidence that the right ATL is more involved in processing of visuospatial information than the left ATL (e.g., Alonso et al., 2021; Mion et al., 2010). Hence, variations in the tasks (visual versus verbal) used to capture the effect of tDCS on creativity might explain the differences. Second, the electrode montage used here was aimed to specifically modulate activity in the left ATL, whereas in the aforementioned studies both ATLs were the target of stimulation. This divergence suggests that the impact of anodal tDCS on RAT problem solving arises specifically when the left ATL is the target of stimulation. In support of this idea, Ruggiero et al. (2018) observed that anodal stimulation of the left ATL coupled with cathodal tDCS of the right ATL reduced RTs relative to sham, even though there was no change in accuracy. Hence, the present study seems to indicate that tDCS montages targeting the left ATL may be able to change performance in the RAT, particularly with anodal stimulation. Further research should be directed to replicate the present finding and to establish the role of right (or bilateral) ATL stimulation and its relation to the type of information required by the creativity task.

In Experiment 2, cathodal stimulation of the right lateral prefrontal cortex resulted in participants having comparable access to both competitors and studied items during the RAT phase, in contrast to the sham group which exhibited the expected impairment following selective retrieval (for related results see Gómez-Ariza et al., 2017; Iglesias-Parro & Gómez-Ariza, 2006; Lezama et al., 2023; Valle et al., 2020a). This finding supports the notion that altering neural activity in the right prefrontal cortex during selective retrieval disrupts inhibitory control over competitors, making them as accessible as non-competitors when it comes to generating solutions. Accessibility to relevant information becomes critical throughout the problem-solving process (e.g., Gómez-Ariza et al., 2017; Gupta et al., 2012; Luft et al., 2018). The present findings contribute to the understanding of how prior inhibition of relevant information may modulate RAT performance (see also Lezama et al., 2023). Furthermore, this tDCS-related finding offers converging evidence supporting the causal role of the right lateral prefrontal cortex in selective retrieval as a source of top-down control that influences memory accessibility and problem solving, including convergent thinking (Penolazzi et al., 2014; Stramaccia et al., 2017; Valle et al., 2020a).

Anodal tDCS over the left ATL was also linked to changes in the pattern of pre-post consistency in theta power observed in the sham group. This suggests that real stimulation specifically modulated theta rhythms. In addition, better resolution of new RAT problems was associated with larger post-pre differences in theta power in the sham but not the real tDCS group, suggesting that tDCS could have changed performance by modulating the pattern of activity in the theta band. Previous studies have related theta oscillations to higher order cognitive functions such as episodic and working memory (WM) processes (Klimesch et al., 2007; Sammer et al., 2007; see Sauseng et al., 2012 for a review) and semantic retrieval (Marko et al., 2019). Moreover, in a transcranial alternating current stimulation (tACS) experiment, Marko et al. induced theta oscillations over the left prefrontal and posterior perisylvian cortex to be either in-phase or anti-phase while participants performed a series of semantic retrieval tasks. Their results indicated that variations in theta-band synchrony modulated semantic retrieval performance (in-phase tACS negatively affected controlled semantic retrieval, while anti-phase tACS improved controlled retrieval but hindered performance on automatic semantic tasks). These results were taken as evidence for the role of theta oscillations in binding semantically related representations, and might support the interpretation that the changes observed here in RS theta after tDCS might be reflecting disturbances in the integration process during RAT problems solving.

Resting-state EEG in Experiment 2 also revealed changes in the pattern of power consistency as a function of tDCS condition. Specifically, prefrontal neuromodulation appeared to eliminate the pre-post stability in the alpha and gamma bands that prevailed in the sham group (as a matter of fact, all frequency bands exhibited consistency across the two RS recordings in this group). Considering the well-established association of the gamma band (along with theta) with episodic encoding and retrieval processes (e.g., Nyhus & Curran, 2010; Griffiths et al., 2019), variations in gamma power after cathodal tDCS of the right DLPFC may arise from the disruption of retrieval-related brain activity. Furthermore, alpha band has been associated with controlled access to information in long-term memory and inhibition of distracting information (Klimesch, 2012). Hence, it is entirely possible that the tDCS-induced changes in cortical excitability are responsible for the loss of pre-post consistency in alpha and that this can mediate the reduction in inhibitory control during selective retrieval. While these are only speculations about the cognitive correlates of these specific changes in brain rhythms in Experiments 1 and 2, they provide complementary evidence (along with performance changes) for specific effects of stimulation over distinct cortical regions of interest for creative thinking.

It is worth mentioning that stimulation of the left ATL did not lead to changes in retrieval-induced impairment (reduced production of competitors as solutions). This result a) replicates previous findings on how inhibitory control during selective retrieval may impact on subsequent problem-solving tasks even unconsciously (creativity: Gómez-Ariza et la., 2017; decision making: Iglesias-Parro & Gómez-Ariza, 2006; Lechuga et al., 2012; analogical reasoning: Valle et al., 2019, 2020a, 2020b) and, more relevant here, b) is consistent with the idea that the left ATL (and its interconnected nodes within the semantic network) do not play a relevant role in exerting top-down control over competing information during episodic retrieval. Thus, only those problems whose solution was never presented (new) were sensitive to the effect of ATL stimulation, so that prior exposure to items (in the case of studied problems) seemed to prevent anodal tDCS from hindering their generation as solutions. While studied words were provided as responses more frequently than unstudied (new) words (this is an expected priming effect; see Valle et al., 2019 for a similar finding in analogical reasoning), they were not affected by anodal tDCS which, however, uniquely disrupted the process of generating unprimed solutions. It is important to note that the problems to be solved with new words in the present experiments essentially correspond to the standard condition in other RAT studies, in which participants solve problems with unprimed solutions (Luft et al., 2018; Zmigrod et al., 2015), and in which neuroimaging and neuromodulation studies have suggested the implication of anterior regions of the left temporal lobe in the generation of creative ideas (e.g., Abraham et al., 2018; Aihara et al., 2017; Chi & Snyder, 2011, 2012; Tik et al., 2018). Hence, it is plausible that prior exposure to solutions, which would increase their activation, may reduce the need to rely on brain regions (such as the ATL) that contribute to semantic integration, which would result in these solutions being less affected by the disruption of neural activity in such regions.

Unlike Experiment 1, participants in in Experiment 2 exhibited a comparable rate of correct responses to new and studied problems regardless of stimulation condition. This shows that right DLPFC stimulation uniquely altered inhibitory control during selective retrieval, which impacted RAT solutions that were competitors. Although previous research has shown that enhanced inhibitory control during retrieval predicts RAT performance (Lezama et al., 2023; Storm et al., 2011), and that inhibition itself may contribute to creative thinking (Palmiero et al., 2022), Experiment 2 failed to provide evidence that disrupting neural activity in the right lateral prefrontal cortex changes RAT performance outside of the specific problems with former competitors as solutions. However, this lack of effect of prefrontal neuromodulation on the production of solutions that had not been previously competitors is not unexpected since previous studies with different tDCS protocols to the one used here also failed to observe general changes in RAT performance (Li et al., 2022; Xiang et al., 2021). It is important to note that none of these previous studies directly assessed or manipulated the strength or presence of competing solutions during problem-solving tasks. Hence, it is possible that the neuromodulation of inhibitory control did not lead to changes in creative performance because the employed creativity tasks did not sufficiently demand such a type of executive control. Additionally, it would be beneficial to examine if the monopolar montage used in Experiment 2 (cathode over the right DLPFC) is effective in modulating

RAT performance when tDCS is delivered online (while participants are engaged in problem solving) rather than offline (as was the case in Experiment 2).

To conclude, an important contribution of the present experiments is that it provides causal evidence of a) the involvement of the left ATL (presumably via integration/combination of ideas) in solving RAT problems and of b) the role of the right lateral prefrontal cortex in downregulating relevant information that could contribute to the generation of creative solutions. It is noteworthy that the present findings support a functional dissociation between the left ATL (as part of a semantic brain network) and the right lateral prefrontal cortex (as part of a cognitive control network). The results from Experiment 1 support the relevance of temporal areas to creativity while opening a door to questioning the possible functional dissociation (or collaboration) between the left and the right ATL, which might also depend on the nature of the creativity task. Along these lines, Salvi et al. (2020) applied HD-tDCS over either the right temporal region (BA22; which is not precisely the same contra-hemispheric region targeted here) or the frontopolar region to compare the effect of this stimulation to that of sham tDCS on performance in the RAT. Their results revealed that, in comparison to sham and left frontopolar stimulation, right temporal stimulation increased hits as well as the use of insight as a resolution strategy. Although Salvi et al. (2020) used a different neuromodulation technique in a more posterior region, which complicates the comparisons between their results and those from our Experiment 1, it suggests an implication of the right ATL during RAT resolution. Finally, Experiment 2 further demonstrated how changes in accessibility of relevant information in memory can subsequently affect the ability to solve creativity problems, as well as the involvement of right prefrontal areas in regulating such accessibility.

While offering valuable insights into the involvement of the left ATL and the right prefrontal cortex in processes that contribute to creative thinking, the present study is not without limitations. Firstly, creativity was only assessed with the RAT. Consequently, it would be necessary to test the generalizability of the present findings in creativity tasks other than the RAT, provided that they require semantic and inhibitory control processes (e. g., story completion task, Lam & Comay, 2020). Second, a dual-electrode (conventional) tDCS montage was used in the present experiments. Even when an extracephalic reference electrode was utilized to minimize its effects on the brain and an active electrode of relatively small size was employed, HD-tDCS could be more suitable for achieving higher spatial precision. Additionally, and following the procedure of previous tDCS studies in our laboratory, both experiments employed a single-blind stimulation protocol. Even when a counterbalance procedure was employed, which precluded the experimenter from being aware of the specific condition to which each problem belonged, a double-blind protocol would have been the preferable option.

Future studies on neuromodulation and creative thinking should include simultaneous recording of electrophysiological brain activity (i.e., EEG/magnetoencephalography) to more precisely determine the neural changes that underlie RAT resolution. Connectivity analyses within and between the different brain networks involved in creative thinking would assist in elucidating of the neurocognitive processes underlying the generation of innovative ideas.

Author contribution

RL: Conceptualization, methodology, data curation, formal analyses, writing – original draft.

CJGA: Conceptualization, methodology, supervision, funding acquisition, writing - review & editing.

MTB: Conceptualization, methodology, supervision, funding acquisition, writing - review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Fundings

The work reported here was supported by the Spanish Ministry of Universities (Grant FPU019/02694) to RL, by grants from the Spanish Ministry of Science and Innovation PGC2018-093786-B-I00 to MTB and PID2021-122979OB-C21 to CJGA, and PID2021-127728NB-I00 to MTB.

Data availability statement

The data that support the findings of both experiments are openly available in OSF at https://osf.io/zyxw2/?view_only=9c5b67b817d14fdbab6d0a592c381812

Supplementary materials

Supplementary materials (Appendix) associated with this research can be found at https://osf.io/zyxw2/?view_only=9c5b67b817d14fdbab6d0a592c381812

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